

ADVANCED DATA ACQUISITION SYSTEMS WITH SELF-HEALING CIRCUITRY

William E. Larson & Curtis M. Ihlefeld
NASA
Kennedy Space Center, FL 32899 USA
William.Larson-1@ksc.nasa.gov
Curtis.Ihlefeld@ksc.nasa.gov

Pedro J. Medelius, Ph.D.
Dynacs, Inc.
Kennedy Space Center, FL 32899 USA
Pedro.Medelius-1@ksc.nasa.gov

ABSTRACT

Kennedy Space Center's Spaceport Engineering & Technology Directorate has developed a data acquisition system that will help drive down the cost of ground launch operations. This system automates both the physical measurement set-up function as well as configuration management documentation. The key element of the system is a self-configuring, self-calibrating, signal-conditioning amplifier that automatically adapts to any sensor to which it is connected. This paper will describe the core technology behind this device and the automated data system in which it has been integrated.

The paper will also describe the revolutionary enhancements that are planned for this innovative measurement technology. All measurement electronics devices contain circuitry that, if it fails or degrades, requires the unit to be replaced, adding to the cost of operations. Kennedy Space Center is now developing analog circuits that will be able to detect their own failure and dynamically reconfigure their circuitry to restore themselves to normal operation. This technology will have wide ranging application in all electronic devices used in space and ground systems.

INTRODUCTION

One of the most important goals for NASA's space program, as it moves into the new millennium, will be to lower the cost of access to space. All of our plans to extend human presence outward into the solar system hinge on that single issue. A key component of overall launch cost is the cost of the processing of both the vehicle and the ground systems. No single breakthrough will help us meet our cost reduction goals. Rather, it must be achieved piece by piece until the goal is met. Technological advances are needed to provide new paradigms in ground processing. One area where technology has been applied to reduce costs is the Ground Measurements System at Kennedy Space Center's (KSC) Launch Complex 39.

The Ground Measurements System (GMS) is used to make engineering measurements at the launch pads, and in the Vehicle Assembly Building. For example, during the stacking of the Solid Rocket Motor segments, the system monitors over 80 strain measurements located inside the Hold Down Posts. (Hold Down Posts are large, hollow metal structures that anchor the Shuttle stack to the Launch Platform.) During the actual launch, the system monitors over two hundred pressures, strains, temperatures and vibrations throughout the Launch Pad area.

The original GMS was installed in the early 1980's, and has supported launches beginning with STS-6. By the mid 1990's the system was no longer supported by the original equipment manufacturer. Although the ability to maintain the system was developed in-house, it became increasingly difficult to find parts due to the lack of availability of components. In addition, failure rates also began to increase as the system aged. The original system had an additional weakness. It required significant manpower to prepare for each launch due to the measurement setup process that required each signal conditioner to be custom matched to it's transducer. When a decision was reached to replace the system, a survey of the marketplace revealed that available signal conditioning systems still had similar measurement setup requirements. Engineers in the Data Acquisition Laboratory felt that technology existed that would allow a more robust and economical system to be developed. The resulting design effort has produced an innovative new system that encompasses measurement setup, signal conditioning, and data multiplexing, transmission and storage. The system will reduce the number of man-hours necessary to process the measurement of 8 Shuttle flights a year by up to 20,000 hours.

SYSTEM DESCRIPTION

The new Ground Measurements System, known as ADAS, for Advanced Data Acquisition System, is designed to acquire transmit, display and record measurement data from transducers in both Launch

Pads and the Mobile Launch Platforms. It is a self-configuring system specifically designed to simplify and automate operational task, such as configuration control, measurement setup and system health checks.

The complete system is presented in Figure 1, where the Mobile Launcher Platform and Launch Pad combinations have been chosen arbitrarily. The system consists of several subsystems that are located within four different facilities, Launch Pad A (LC-39A), Pad B (LC-39B), Vehicle Assembly Building (VAB), and Launch Control Center (LCC), some of which are separated by miles. One control Ethernet and five independent data networks link the system.

Measurement data and system status will flow generally left to right, originating at the measurement transducer and Universal Signal Conditioning Amplifier (USCA) and flowing toward the LCC. Command information generally flows right to left, originating at the workstation in the LCC and flowing towards the measurement facilities. Command, status, and display information are transmitted on the Ethernet. The high-speed measurement data flows one way, from the Advanced Data Acquisition System chassis (ADAS) to the LCC on one of the five private fiber-optic-data lines.

The GMS Upgrade was designed as a "measurement

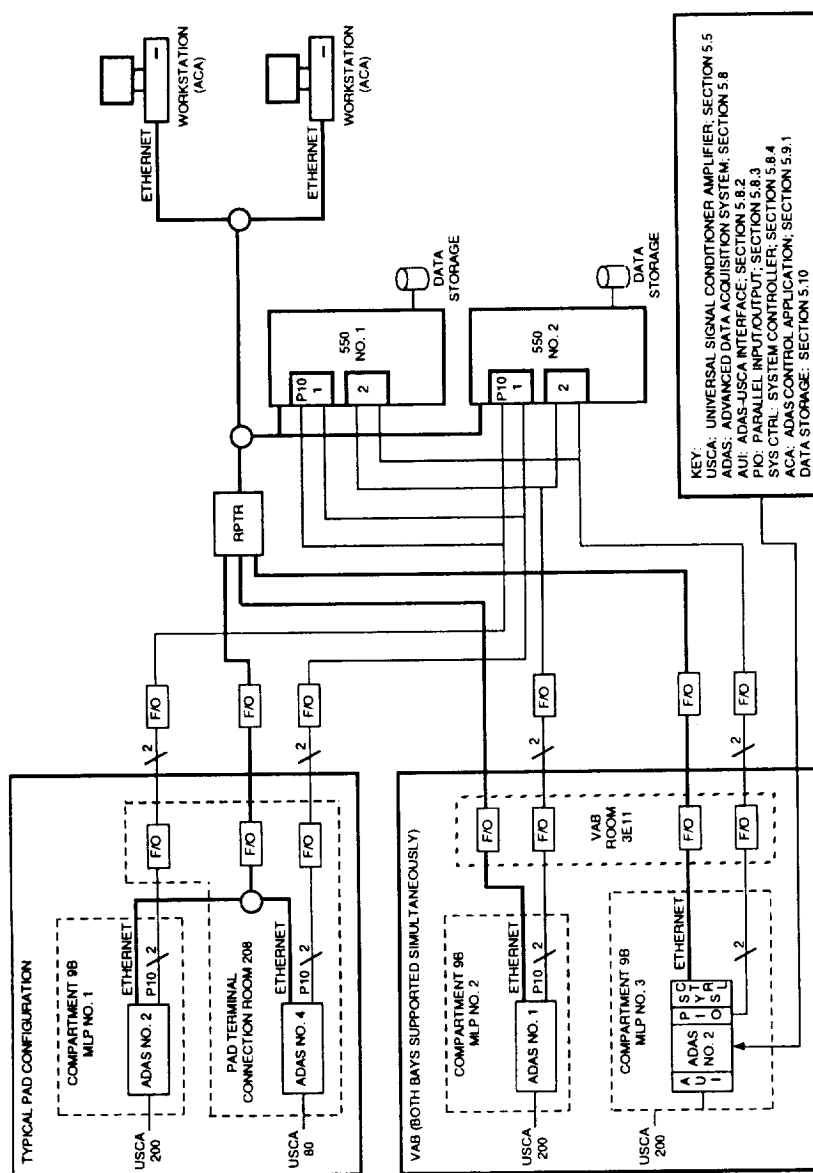


Figure 1 GMS Block Diagram

driven" data acquisition system, which means the act of plugging a transducer into the system automatically generates a sequence of events culminating in data flow to the LCC. This was achieved by electronically storing all of the information necessary for identifying and setting up a measurement into an external memory device (called "Tag RAM") connected to the transducer. When any such transducer is connected to a USCA, the USCA reads the Tag RAM providing all the information USCA needs to signal condition the transducer and digitize its data. The USCA signals the VME-based chassis (ADAS) that a measurement has been connected and it, in turn, passes the new measurement information on to the Host Workstation. The software called the ADAS Control Application (ACA), executing on the Workstation contains the intelligence to use the Tag RAM data. It coordinates the setup of the entire system upon detection of a measurement. It also provides a user interface that allows a user in the LCC to easily monitor the system and make changes to equipment at the measurement sites, such as USCA filter changes, ADAS channel enabling/disabling, and many others.

The following sections further detail the functionality of the system, including the automatic sequence of events that occur as a result of system configuration changes. This will be accomplished by a description of the subsystems, their decomposition into functional or block diagrams, and a description of data flow.

SUBSYSTEM DESCRIPTIONS

TagRam

based device designed to be a transducer's electronic calibration sheet. The Tag RAM components are all installed on a small (1-inch by 1-1/4inch) printed circuit card. The Tag RAM is typically installed in the molded end of the "pigtail" cable, which adapts the transducer's connector to the USCA input connector. The measurement information and the transducer's calibration data is loaded into the Tag RAM prior to measurement installation using a serial data communications protocol and a PC-based setup program. The Tag RAM then contains all of the information necessary to allow a USCA to configure itself for the transducer to which it is connected.

Universal Signal Conditioning Amplifier

The Universal Signal Conditioning Amplifier (USCA) is the key technology component in the Data Acquisition System. It automatically configures itself to match the transducer to which it has been connected. This reduces the time that is required to set up a measurement to seconds (original system required 2-4 hours). USCA contains multiple programmable components that allow this automated configuration to take place. The design consists of a programmable 16-bit D/A converter for transducer excitation, a programmable gain amplifier, a 16-bit A/D converter, a Digital Signal Processor for filtering and data linearization, and an output stage that provides both analog and digital outputs. The major modules of USCA are shown in Figure 2.

Once USCA has read the setup information in the Tag RAM, it is ready to configure itself for operation. The

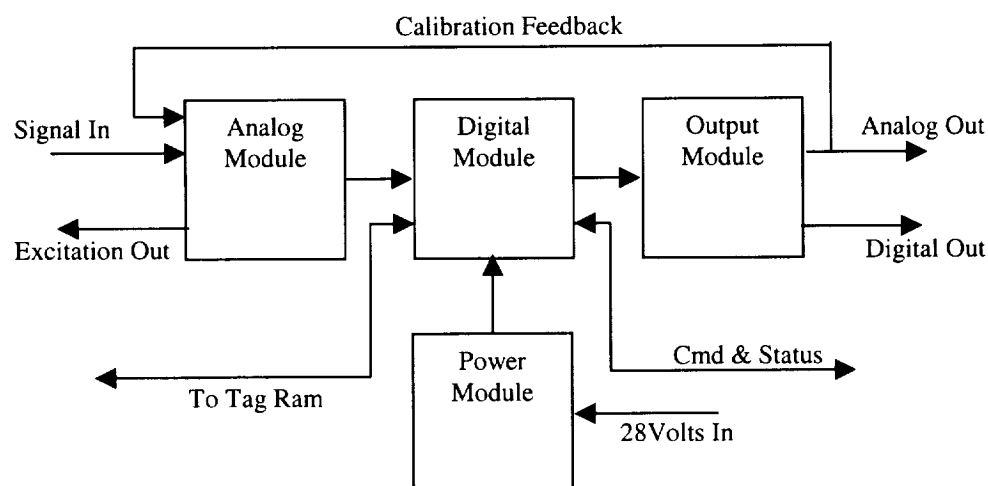


Figure 2. Simplified USCA Block Diagram

The entire measurement system revolves around the contents of an external memory device called the Tag RAM, which is a tiny microcontroller and EEPROM-

excitation module is commanded to the output levels that were read from the Tag RAM. This dual channel, 16 bit, D/A converter is capable of providing a highly

regulated voltage or current output. The module allows the selection of an excitation voltage between 0 and 27VDC with a resolution of about 500 μ V. In current mode, the module can provide currents between 0 and 2.5 mA with a resolution of better than 0.1 μ A. A bypass mode is available for both the voltage and current modes, which allows the USCA to pass through the output of the remote power supply, which is nominally 28VDC. The accuracy of this mode is limited to the resolution and stability of the remote supply.

USCA also configures its input module based on the information read from the Tag RAM. USCA contains two highly stable programmable gain amplifiers (PGA) that include transient and over voltage protection. The circuits have been designed to provide a DC to 5kHz passband that is flat to within 0.2 dB, with a -3 dB bandwidth of 6.5kHz. The programmable gain stage can select gains between 0.25 and 2000, allowing USCA to accept full-scale inputs from 30V down to 5mV. An anti-aliasing filter is then applied to the signal before it is sampled at 20k Samples/sec by the 16-bit A/D converter.

A Digital Signal Processor (DSP) controls both the excitation and input modules. The DSP performs multiple tasks to insure the accuracy of the measurement. Taking advantage of the dual channel PGA and A/D converter, the DSP performs a continuous calibration check. The inactive A/D channel samples a highly stable voltage reference (better than 1ppm/ $^{\circ}$ C) and digital gain adjustments are made by the DSP to correct for errors. Once that A/D channel is calibrated, it is swapped with the other A/D channel so that it can be calibrated. This entire process takes place continuously and is transparent to the user. However, it does allow USCA to constantly check on its health and report any serious deviations back to the host CPU immediately.

The DSP also provides the USCA with many other features. Using the linearization coefficients downloaded from the Tag RAM, up to an eighth order equation can be performed in real-time. Another use of the coefficients will allow USCA to perform frequency-based measurements. To eliminate noise in the measurement, a 127th order digital filter can be applied to the data. Memory space has been set aside in the USCA to accommodate seven sets of coefficients for standard high pass or low pass digital filters. An eighth memory area has been set aside to allow the user to download custom filter coefficients from the host computer. Using commercially available

filter design packages, passband and notch filters can be designed and downloaded. Another feature that the DSP allows is the dynamic control of the excitation module. This gives USCA the ability to do more than simple DC excitation. It can provide pulsed excitation with various duty cycles and amplitudes. This can be useful when making strain measurements where high excitation voltages may cause a self-heating problem. Pulsing the excitation can significantly reduce the self-heating while still allowing an accurate measurement to be made.

Once the DSP has completed the signal processing functions, it also handles the data output functions. USCA has two data output paths, one is analog and the other is digital. The analog output can select from several output ranges. Ranges of 0-5VDC, 0-10VDC, \pm 5VDC and \pm 10VDC are selected based on the contents of the Tag RAM. A dual channel 16-bit D/A converter performs the output function. The DSP checks and calibrates the analog output of the USCA in the same manner as the input module described above. A serial port on the DSP is used to send digital data back to a serial data multiplexer that will be described in the next section of the paper. The serial port supports data transfers at 460 kbits/sec over distances of up to 3000 feet. Both the analog and digital outputs are electrically isolated from the input and the 28V input power supply.

To minimize signal noise it is desirable to mount USCA as near as possible to the transducer. Due to the harsh environment of the Launch Pad, the USCA circuit boards are mounted in a hermetically sealed cylindrical anodized aluminum enclosure. Interconnects between the boards are handled by sandwich style connectors capable of withstanding several hundred G's. The enclosure radiates the heat so well that USCA can operate in an environment between -20 $^{\circ}$ to 50 $^{\circ}$ Celsius.

Advanced Data Acquisition System Chassis

The Advanced Data Acquisition System Chassis is designed to receive digital data from up to 416 USCA'S, time stamp and multiplex this data, and transmit it to the LCC. It also provides control for the USCA'S, automatically or through commands sent by the ADAS Control Application (ACA). It is based on L-3 Telemetry and Instrumentation's System 550 chassis that consists of specialized modules connected to a standard VME bus and a high-speed-data bus called the MUXbus. The complete ADAS chassis contains: a VME system controller, a MUXbus arbiter, up to thirteen ADAS/USCA Interface (AUI) modules,

a Time Code Decoder/Generator, and a Parallel Input/Output module.

The ADAS/USCA Interface (AUI) is handled by a VME circuit board designed by NASA and Contractor engineers with support from a private industry partner. Each AUI supports 32 channels of USCA measurements, so a fully configured ADAS chassis will support 416 USCA channels. It has two major subsections, the low speed USCA command and response interface and the high-speed data acquisition interface. The low speed section is integral to the automated capabilities of the ADAS. It has circuitry that allows it to automatically detect the presence or absence of a USCA. It passes commands to and continuously receives status from each USCA connected to it. If desired, it also uses the command pathway to synchronize the USCA sample clocks to within 2 μ sec. A non-volatile memory area is maintained on the board for each USCA channel, so that the data address tag to measurement name table is not lost during a power outage.

The high-speed section of the AUI board receives the digital output from each USCA's Digital Signal Processor. Each 16-bit sample from USCA is transmitted in 8-bit segments with Start, Stop and Parity bits added. The parity alternates between even and odd to allow the receiver to maintain synchronization. AUI time stamps each sample it receives and places the data on the high-speed data bus. The time stamps can also be placed on the high-speed bus with every sample, or every nth sample, based on the system operator's needs. Once the data is on the high-speed bus the system architecture allows the system engineer to have several data distribution options. For data display, a computer workstation can acquire snapshot or grab sample data via the Ethernet interface on the system controller board. If the ADAS chassis is located in an environment that is not too harsh, a RAID disk and controller can be added to the system to record the data and time. In Kennedy Space Center's application, the ADAS chassis is located in the harsh vibration environment of the Mobile Launch Platform, which is buffeted mercilessly during a Space Shuttle launch. This requires that we send the data to a similar VME chassis located in the Launch Control Center. This is accomplished by augmenting the Parallel Input/Output card with a high-speed interface to a serial data transmitter that is then interfaced with fiber optic transmission equipment. The converse is applied in the Launch Control Center (LCC) where the data and time end up back on the LCC system's high-speed data bus. Once on the LCC system, data is

distributed to display workstations and the RAID disk as discussed above.

ADAS Command Application

The system software, which is called the ADAS Control Application (ACA), pulls all of the hardware together to provide the user with a highly automated, self-configurable data system. Adding a new measurement to the data system is as simple as plugging in a new measurement. As mentioned above, USCA configures itself to match the transducer to which it has been connected. This happens automatically when the USCA is connected to an AUI channel. AUI detects the presence of the USCA and reads the measurement information in the Tag RAM via the USCA. This measurement information, which contains a unique measurement identifier, or name, assigned by the measurement engineer and loaded into the Tag RAM prior to field installation, is passed back to ACA executing on a Workstation in the LCC. This program is the overall system supervisor and manages the system configuration databases as well as providing the operator command and status displays. The program assigns a unique 16-bit tag to this new measurement, which will be used by the AUI card to identify data that it is placing on the high-speed data bus. This tag is used throughout the system to identify this measurement's data whether it is for data display or data recording. But, this is all invisible to the operator of the system. All the operator needs to know to observe or record data coming back from the field is the measurement name. The software makes the connection between names and tags. Since the system has configured itself and recorded its configuration in a database, the only thing the operator must do is create the data display screens needed for a test. PC's that use screens created using LabView, a graphical programming language from National Instruments, handles data displays. The operator again selects measurements for display by using the measurement's name. The PC acquires the data over the Ethernet from the ADAS chassis.

ACA also has a command interface that allows the user to monitor or modify the setup of the system. Any part of the system setup, which was performed by the automated portions of the software, can be overridden or changed by the operator. By specifying a measurement number, the software displays a page of data that contains all of the current USCA setup parameters. The user can make any changes needed to the parameters and then write them, via AUI and USCA, into the Tag Ram for that measurement, so that the changes will be enacted automatically in case of a power interruption. To ease the operator workload,

measurements can be assigned to groups so that, where applicable, commands can be issued to a group of measurements instead of individually. The user interface allows the operator to initiate several diagnostic commands. For example, an individual USCA or group of USCAs can be placed in a calibration mode where they output a calibrated percentage of their full-scale output. Similarly, individuals or groups can be commanded to close a solid-state relay located in the Tag Ram to shunt a known resistor value across a bridge type measurement. ACA also provides menu options that allow the database of measurements to be maintained and reports to be generated.

IMPLEMENTATION & SPINOFFS

The Advanced Data Acquisition System is being phased into operation at KSC's Launch Pads. Both Pads have the system in place and the Mobile Launch Platforms will be operational in the near future. The technology has been a great success, providing more accurate measurements at a lower operational cost. When fully implemented the system will save over 10,000 man-hours annually.

Core elements of the technology have been "Spun-off" into the commercial marketplace. The USCA and AUI have been integrated into the product line of L-3 Telemetry and Instrumentation, of San Diego California. Their version of the system, called the ADAS 5000, allows the benefits of this technology to be made available to the commercial sector.

FUTURE ENHANCEMENTS

KSC has not stopped looking for ways to improve the system further. All signal conditioning systems have significant analog circuitry that is critical to its operation. Degradation or failure of these analog components requires the replacement of a USCA in the field. These replacements drive up the costs of operations.

In fact, analog circuit failures impact a wide variety of systems at KSC's launch complex. Reducing or eliminating these failures would have a significant impact on operations costs throughout the Space Center. Advances in Field Programmable Gate Arrays (FPGA) and Programmable Analog Integrated Circuits (PAIC) have opened up the possibility of designing circuits that can be dynamically reconfigured. Development of a new Smart Signal Conditioning Amplifier (S²CA), which takes advantage of this technology, has reached the prototype stage of development.

Self-Healing Circuits

The self-healing capability of the S²CA will result in increased benefits to satisfy the aerospace industry's need to reduce operations cost, to accelerate processing time and to provide reliable hardware at a reasonable cost. Among the benefits provided by the S²CA are:

- Electronic health self-check
- Device/system self-calibration
- Electronics and function self-repair
- Failure detection and prediction
- Power management, for reduced power consumption

The incorporation of FPGA and PAIC has resulted in a highly flexible circuit architecture capable of reconfiguring itself upon internal or external control. Detailed evaluation of the mean-time-between-failures (MTBF) resulted in the determination of the components for which "*spare parts*" had to be made available. A modular approach on the design has resulted in three distinct, although closely interfaced, functional sections:

1) Analog Signal Section

The Analog Signal path addresses the issue of signal redundancy and signal integrity without taking the traditional approach of providing total hardware redundancy for every channel and every function block of a data acquisition system. The architecture design was driven by the need of self-calibration and verification capabilities. Data acquisition systems used in spacecrafts need to have the means to perform automated calibration without external intervention, since the quality of a measurement is directly related to the ability of the system to guarantee a proper calibration through the life of the process being monitored. The capability of the data acquisition system to perform system health checks, failure detection and failure prediction as well as to have automated self-repair capability plays a paramount importance in systems where operator intervention is not an option. Traditional approaches to these problems have been based in total hardware and software redundancy to overcome failures, at a significant increase in cost, weight, size and power requirements.

The analog section has incorporated a concept we have called "*spare parts - tool box*". As with any process that has identifiable critical components, the areas of the data acquisition system's analog signal path with specific reliability problems have been identified and assessed. An initial reliability

assessment based on data acquisition system exposure to external conditions was implemented, where areas such as signal inputs and outputs were considered high-risk areas, while internal areas of the system not exposed to the external environment were considered lower risk areas.

Based on the reliability rating given to specific areas, the system was allocated a "tool box" with n number

of "spare parts" (components) necessary to guarantee continued operation of the system. Areas with higher probability of external stress are assigned a greater number of "spare parts" than areas well protected by the system. The overall diagram of the design architecture for the analog signal path is presented in Figure 3.

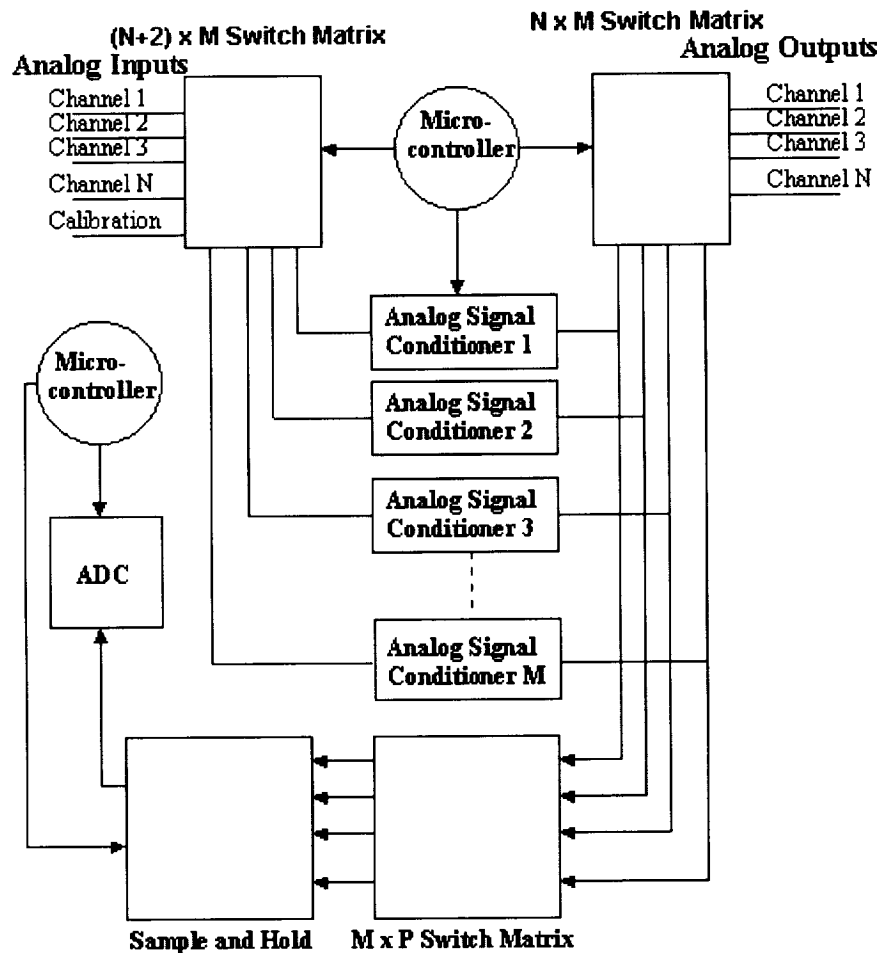


Figure 3. Smart Signal Conditioning Amplifier (S²CA) analog signal path.

The architecture is defined as a series of analog signal inputs to the system (in this case defined as N). Two internal inputs are defined to provide the self-calibrating capabilities. These are internally controlled by the system to perform the calibration and verification functions.

A matrix of analog switches, individually addressable by the internal controller, is used for connecting the

external inputs to the internal bus and subsequently to the signal amplifiers and conditioners. The analog switch matrix configuration is used extensively in the analog path implementation of the S²CA. This approach results in the flexibility to reconfigure any section of the analog circuitry based on its health. The analog switch matrix approach allows external and internal bus lines to be configured in real-time by

the controller to provide alternate path to any analog signal.

The internal bus is comprised of M lines, where M is defined as:

$$M = N + SL1 \quad \text{where}$$

N = number of external inputs
SL1 = number of "spare parts"

The configuration of the matrix switches is normally defined and controlled by the internal microcontroller. The analog signal conditioners are responsible for processing the input and calibration signals, and are selected, configured, monitored and removed from the system (when a problem is encountered) by the micro controller in the system. The "spare parts" in the "tool box" are not used by the system until a specific need arises due to a component failure

The S²CA has a preamplifier section with user-selectable gain, filter circuitry, and an output stage with configurable gain. By using this capability, the "tool box" consists of generic analog signal conditioner "spare parts" that can be incorporated in the circuit and reconfigured immediately to maintain the required signal integrity. The outputs of each of the signal conditioners are connected to a second internal analog signal bus whose function is to apply the conditioned signals to the Output Signal Switch Matrix as well as the Sample and Hold circuitry. This matrix connects the internal bus to the User's accessible output lines. The size of the two-dimensional matrix is based on the number of primary and "spare part" signal conditioners (in this case M) and the number of primary and "spare parts" Sample and Hold circuits (in this case R). The number R is developed from the following equation:

$$R = N + SL2 \quad \text{where}$$

N = number of external inputs
SL2 = number of "spare parts"

The selection of the number and type of spare parts is derived from the reliability studies for each individual section of the system.

The Sample and Hold (S&H) section provides the synchronous sampling of the analog input and calibration signals. The output from each of the S&H circuits is then routed sequentially to the Analog-to-

Digital Converter section for data digitization using an analog switch matrix. This provides the system with the flexibility to select and match any input to any output.

The calibration circuit is used to achieve real-time continuous calibration and verification of the analog channels. This feature is used in conjunction with the analog switch matrix and the analog signal conditioners to determine whether signal health and accuracy is within the requirements of the system and if not, to set an alternate path for the system that satisfy the requirements.

2) Digital Signal Section

The Digital Module (DM) provides control, monitoring, and processing of the analog signals. The basic architecture of the Digital Module consists of one or more processors, and Field Programmable Gate Arrays (FPGAs). The DM provides redundant control and monitoring of the critical sections of the S²CA and it is designed for low power consumption. It also monitors the health of the system by processing pre-defined measurements and/or trends and automatically makes adjustments to the system for channel failures, temperature compensation, and gain calibration. The design architecture for the digital signal path is presented in Figure 4.

The main functions of the DM section are:

- Detect signal path failures and perform self-repairs.
- Perform periodic calibrations on the Analog Module.
- Automatically detect system degradation and predict potential failures.
- Control the operation of the analog section by means of the analog switches.
- Perform real-time digital signal processing.

The DM incorporates multiple processors, including a master and one or more slaves. In the event one of the processor fails, another processor assumes the tasks of the failed processor. Continuous handshaking among processors ensures rapid detectability and recovery from failures, including those resulting from Single Event Upsets (SEUs).

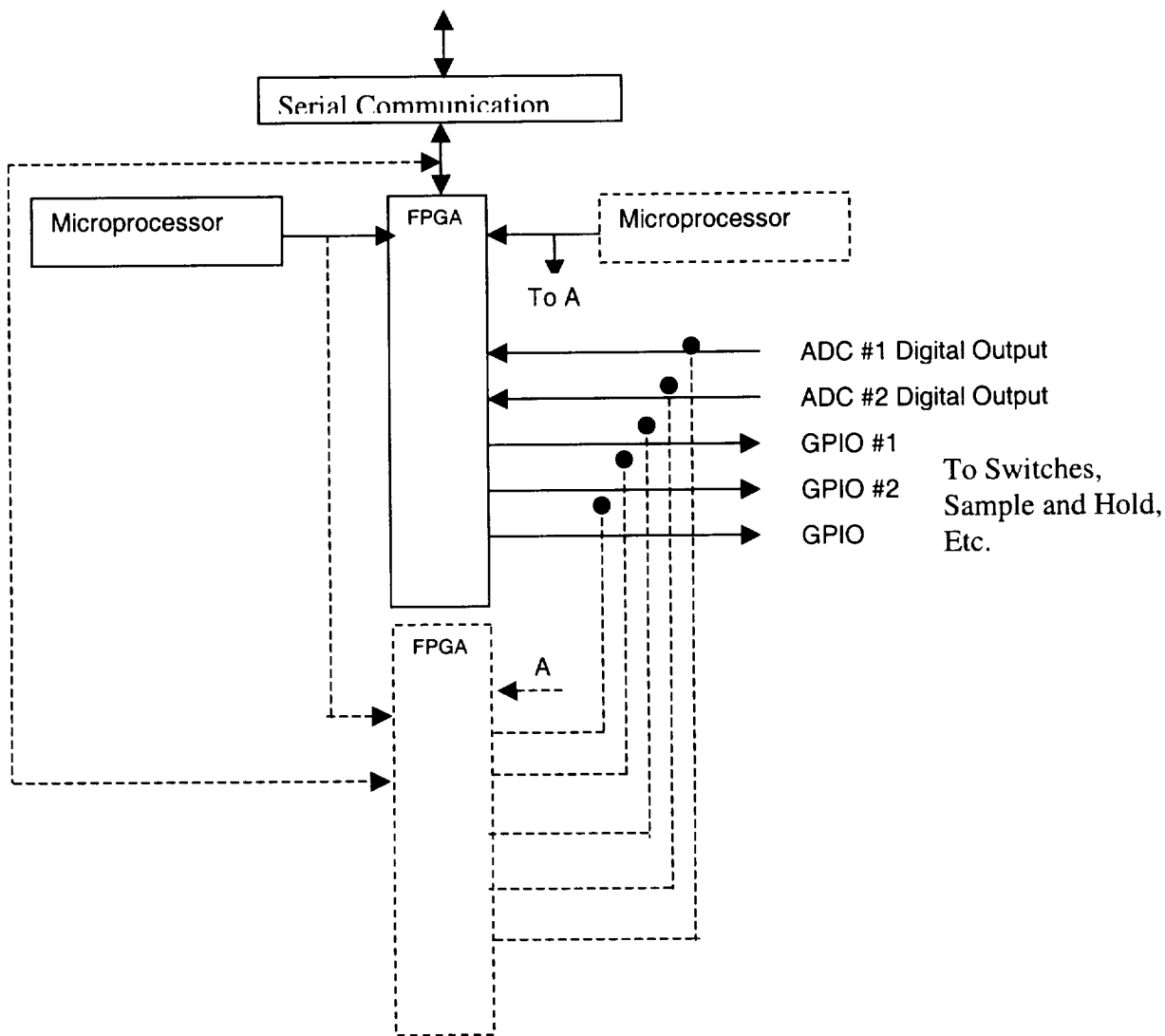


Figure 4. Smart Signal Conditioning Amplifier (S²CA) digital signal path.

3) Power Management Section

It is very important to dynamically reduce power consumption as needed, especially on long missions where power availability is limited. Proper power management results in reduced battery weight and reduced heat generation.

The power management covers three main functions (see Figure 5):

- a) **Power Supply Monitoring Circuit** – This section provides over-voltage and under-voltage monitoring/protection, provides surge detection and suppression, and performs noise monitoring and filtering.

- b) **Current Monitoring Circuit** - This section provides power supply current consumption information from each area of the system. It also detects over-current conditions indicative of a malfunction, which will be for decisions regarding system reconfiguration, and system reset.

- c) **Power Supply Dedicated Controller** - Provides monitoring and control capabilities of the different components in the power management section, as well as provides an independent assessment of the main processor's health by monitoring specific parameters (current consumption, periodic scheduled communication between them,

etc.) This section is used primarily to dynamically control the application or

removal of power to various section of the circuitry based on their active/inactive state.

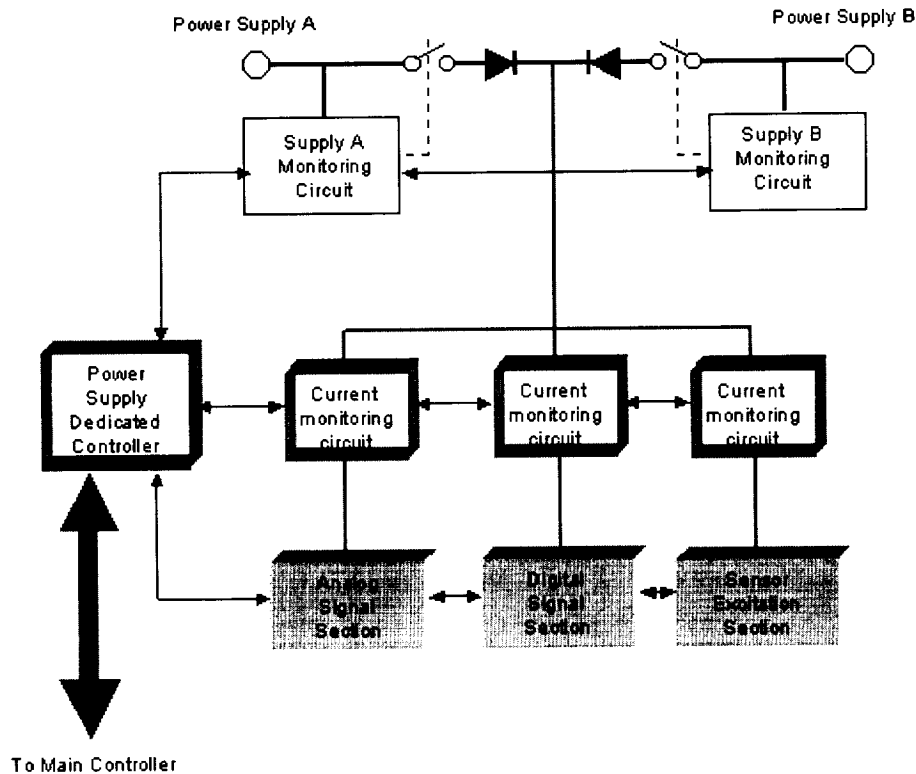


Figure 5. Smart Signal Conditioning Amplifier (S²CA) power management section.

CONCLUSIONS

Design advances in Data Acquisition Systems have had a significant impact on the reduction of cost in the ground processing of human space flight missions. The USCA coupled with the ADAS represent a significant advancement in the state-of-the-art. However, new developments like the S²CA will help drive costs down further by reducing the number of failure related hardware replacements. The concept of building "*spare parts*" into a design will migrate to many other ground and flight system designs, improving their reliability and providing more robust systems for space flight and industry.